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NEPENTHE STUDY

Technical Report No. 7

SEISMIC ARRAY PROCESSING TECHNIQUES

Prepared by

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TEXAS INSTRUMENTS INCORPORATED
Services Group
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ABSTRACT

The Nepenthe process and some simple modifications are investigated to determine their potential value as offline surface-mode signal-extraction techniques. The techniques have been applied to long-period noise, with a known signal added at various strengths. The processor output is compared with the known signal input to judge performance. The results are compared with a bandpass filter.

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SECTION I

INTRODUCTION

The Nepenthe process, a single-channel technique for suppressing long-period noise, was developed by Simons, Weber, and Travis as an attempt to use the stationarity of long-period noise.[1] Briefly, the Nepenthe process uses a group of nonoverlapping segments of long-period noise to estimate a noise amplitude spectrum which it then subtracts from the amplitude spectrum of a segment to be treated. The resulting difference spectrum (with negative values set to zero) is combined with the unaltered phase spectrum of the original segment and displayed as a time trace, after which the entire process advances one segment. Figure 1 is a diagram of the processing sequence.

The Nepenthe was investigated to determine its value as an offline surface-mode signal-extraction technique.

In evaluating the process, various modifications were tried, including:

- Bandpass-filtering (0.02- to 0.06-Hz passband) all data processed to eliminate the microseismic peaks of the estimated noise spectrum and concentrate the processes on the signal band

- Applying a 75 percent confidence limit for the noise spectrum to determine the process' sensitivity to changes in the upper limit

- Using a constant value for the number of degrees of freedom and comparing the results with the spectrum obtained using maximum-likelihood estimators for the degrees of freedom

- Using a comparison process rather than a subtraction process when applying the estimated noise spectrum to the treated segment

- Trying to prevent discontinuities at segment boundaries by adopting a segment length of 512 samples composed of 256 samples of data (491.52 sec preceded and followed by 128 zeros to taper the groups of time-domain data into one another at the boundaries

- Shifting the signal in time through the noise to determine whether the Nepenthe process is sensitive to the location of the signal in the segments

A zero-phase bandpass filter (0.02- to 0.06-Hz passband) was applied to the data and output with a difference trace to compare Nepenthe with a bandpass filter alone. Synthetic data were generated so that noise and signal spectra were known and so that any distortion of the signal by the various processes would be revealed. The amount of signal distortion is indicated by the difference trace, which is the processed output subtracted from the signal that was placed in the noise.

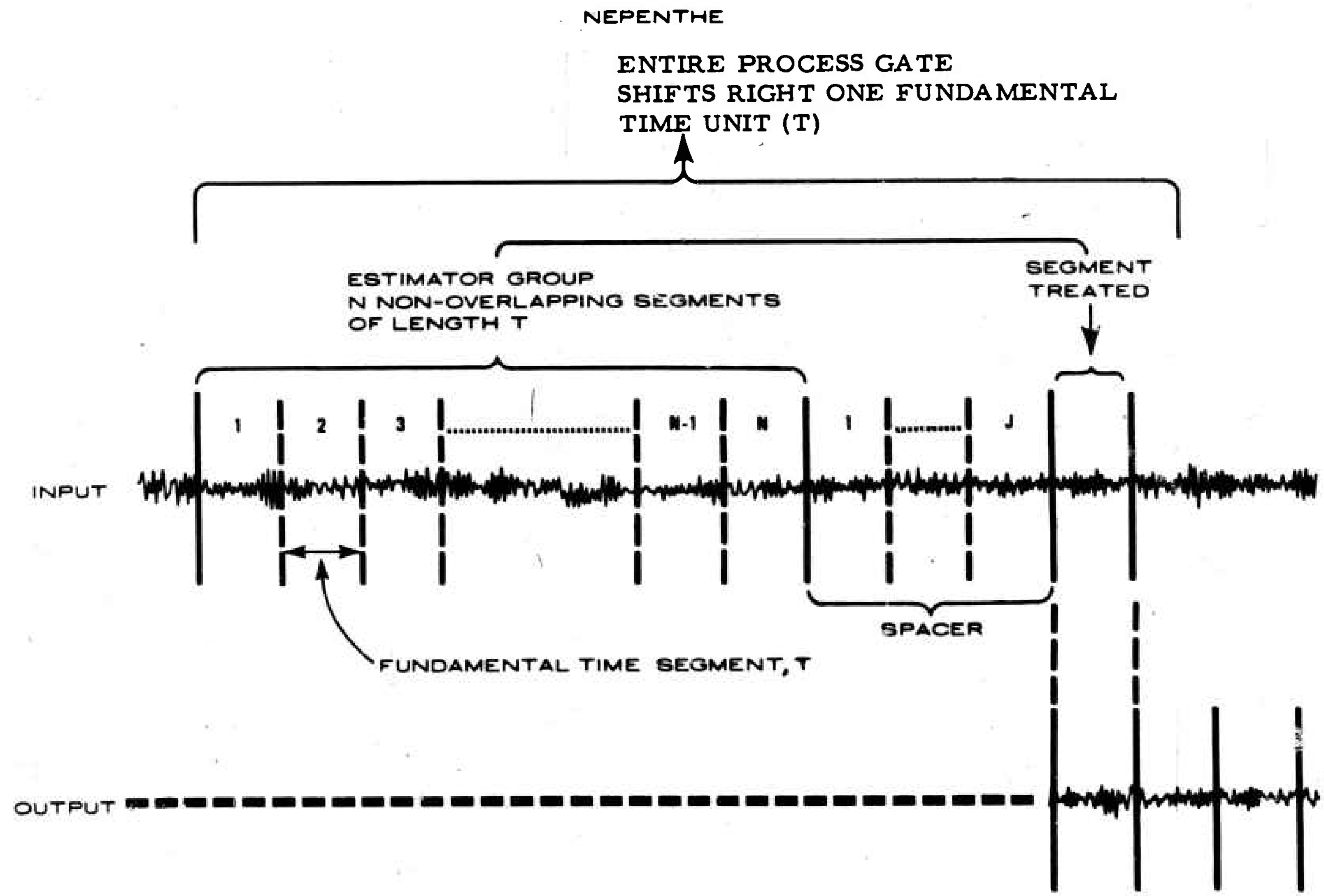

Figure 1. Nepenthe Data Processing Sequence

SECTION II

DESCRIPTION OF NEPENTHE PROCESS

A. NEPENTHE SPECTRUM ESTIMATION

As originally conceived, the noise amplitude spectrum estimation assumes normally distributed noise with zero mean. In this case, the real and imaginary parts of the discrete Fourier transform S (f) are also normally distributed with zero mean. If

$$P(f) = \text{Real}^2 [S(f)] + \text{Imag}^2 [S(f)]$$

then P (f) is distributed as a scaled chi-square variable $a\chi^2(b)$ where

a = scale factor

b = number of degrees of freedom for χ^2 distribution

The process uses maximum-likelihood estimates for a and b. The derivation is given in reference 1, and the equations are

$$\hat{a} = \frac{\hat{u}}{\hat{b}}$$

$$\hat{b} = \left\{ \ln \left[\frac{\hat{u}}{\left(\prod_{i=1}^{N} P_i(f) \right)^{\frac{1}{N}}} \right] \right\}^{-1}$$

where

N = number of nonoverlapping segments in estimation

$P_i(f)$ = sum of squares of real and imaginary spectrum at frequency f and segment i

$$\hat{u} = \frac{1}{N} \sum_{i=1}^{N} P_i(f)$$

After the calculation of the a's and b's, the estimated spectrum is the square root of the upper 90 percent limit of this distribution.

B. NEPENTHE TECHNIQUE

The entire Nepenthe process (Figure 1) works as follows:

- Discrete Fourier transforms S(f) of N nonoverlapping segments of equal length T are computed using the fast Fourier transform algorithm
- At each frequency and segment, the sums of the squares of the real and imaginary spectra are computed:

$$P_i(f) = \text{Real}^2\,[S(f)] + \text{Imag}^2\,[S(f)]$$

- The $P_i(f)$ are smoothed across segments by a Hanning function
- For each frequency, the maximum-likelihood estimators $\hat{a}$ and $\hat{b}$ are computed and $\hat{a}\chi^2\,(\hat{b}{:}90)$ is estimated, where $\chi^2\,(\hat{b}{:}90)$ is the upper 90 percent point of a chi-square distribution with $\hat{b}$ degrees of freedom and $\hat{a}\chi^2\,(\hat{b}{:}90)$ is the upper 90 percent point for the $P_i(f)$ across N segments at freque r f
- The square root of the $\hat{a}\chi^2\,(\hat{b}{:}90)$ for each frequency is then taken as the noise amplitude spectrum
- The segment to be treated — which is also of length T and a fixed number of segments ahead of the estimator group — is also Fourier-transformed, A(f). For the experiments described in this report there was no gap (i.e., J=0) between the estimation group and the segment to be analyzed. This caused no difficulty because the signal was added at a known time. The amplitude B(f) and phase θ(f) spectra are computed, where

$$B^2(f) = \text{Real}^2\,[A(f)] + \text{Imag}^2\,[A(f)]$$

$$\theta(f) = \tan^{-1} \frac{\text{Imag}\,[A(f)]}{\text{Real}\,[A(f)]}$$

- The estimated noise amplitude spectrum is then subtracted from the treated segment's amplitude spectrum B(f). If the difference at a particular frequency is less than zero, that amplitude is set equal to zero; the phase spectrum is unchanged

- The difference spectrum and the unaltered phase spectrum $\theta(f)$ are then inverse transformed and displayed as a time-domain trace
- The entire process is advanced one segment and repeated

C. DATA

To determine the effects of the Nepenthe technique on a portion of data, a signal with a known spectrum (Figure 3) was inserted into a noise train of known characteristics (Figure 2) at S/N (signal-to-noise) ratios of 4:1, 1:1, 1:2, 1:4, and 1:8. (The S/N ratios used are ratios of the mean-square amplitudes of both signal and noise.)

The signal is a vertical-trace 32-min-long Rayleigh wavetrain from the Rat Islands, which was recorded at Tonto Forest Observatory on June 22, 1969. The noise is a 130-min record from TFO recorded by Texas Instruments on July 27, 1969. The sample interval is 1.92 sec/sample. In the noise spectrum estimation, 11 segments of 256 points were used so that the estimated noise spectrum would compare with the 11 to 18 segments and 512-sec lengths used in the original paper.[1] Figure 4 shows plots of the noise and the signal.

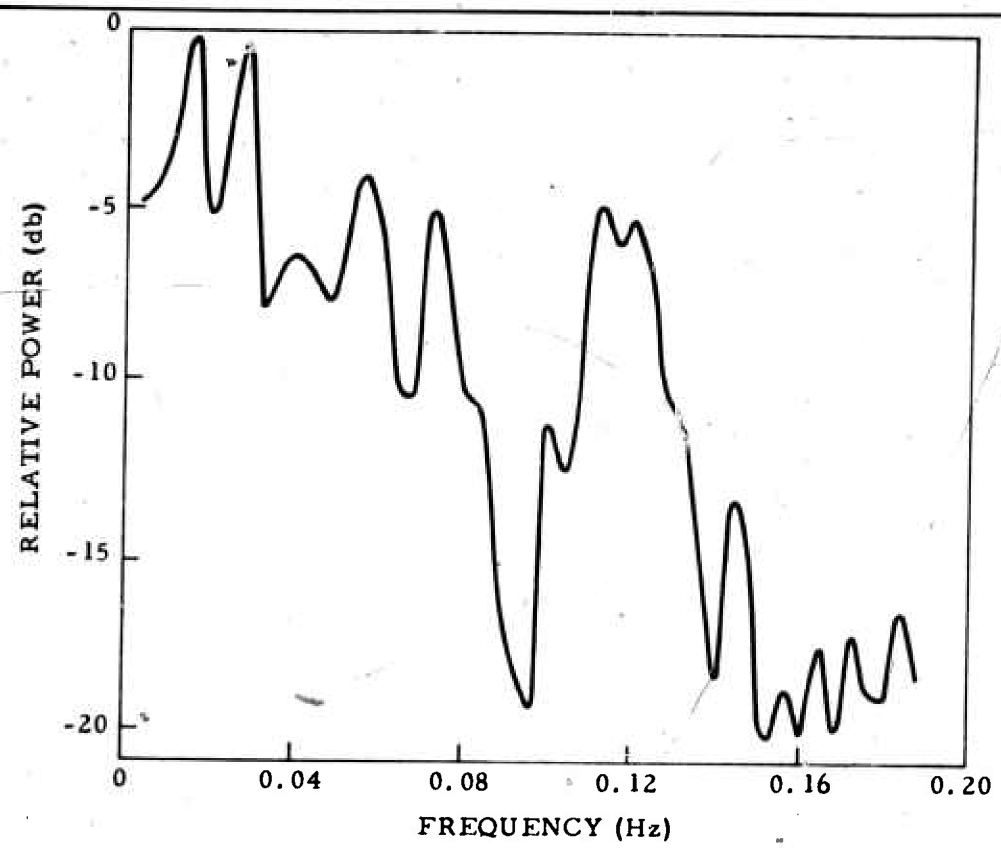

Figure 2. Noise Spectrum of 1024 Samples (1966.08 sec)

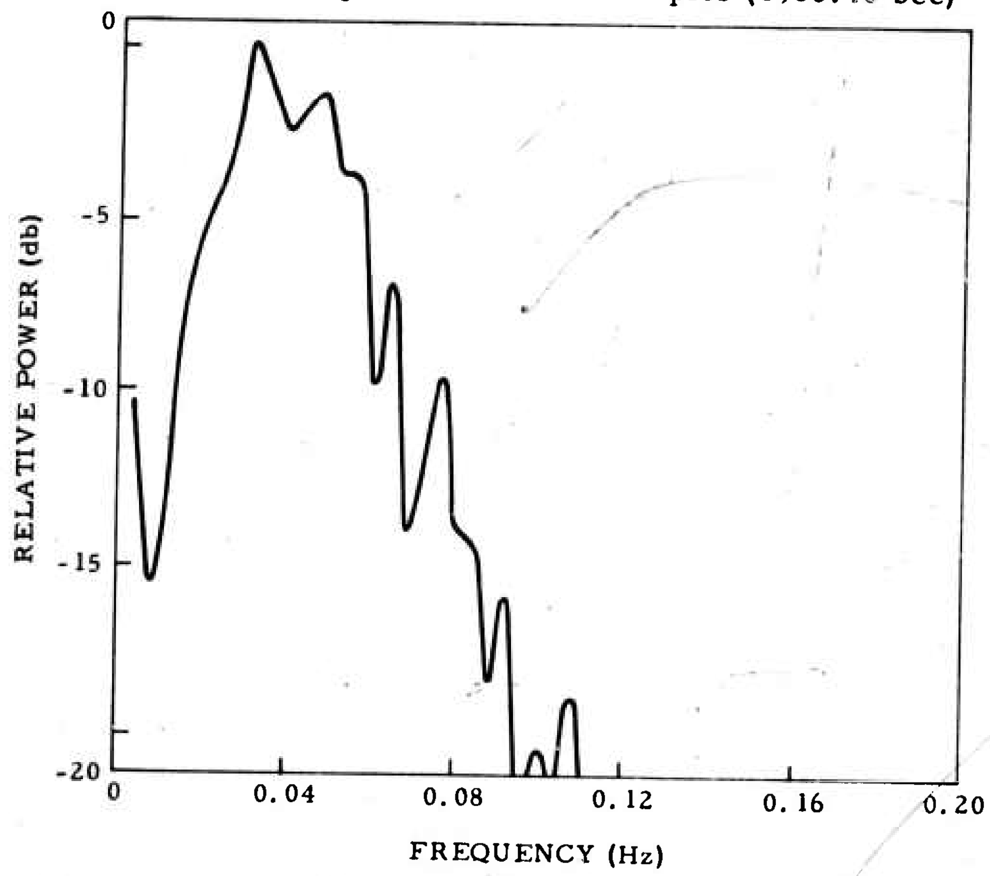

Figure 3. Signal Spectrum of 1024 Samples (1966.08 sec)

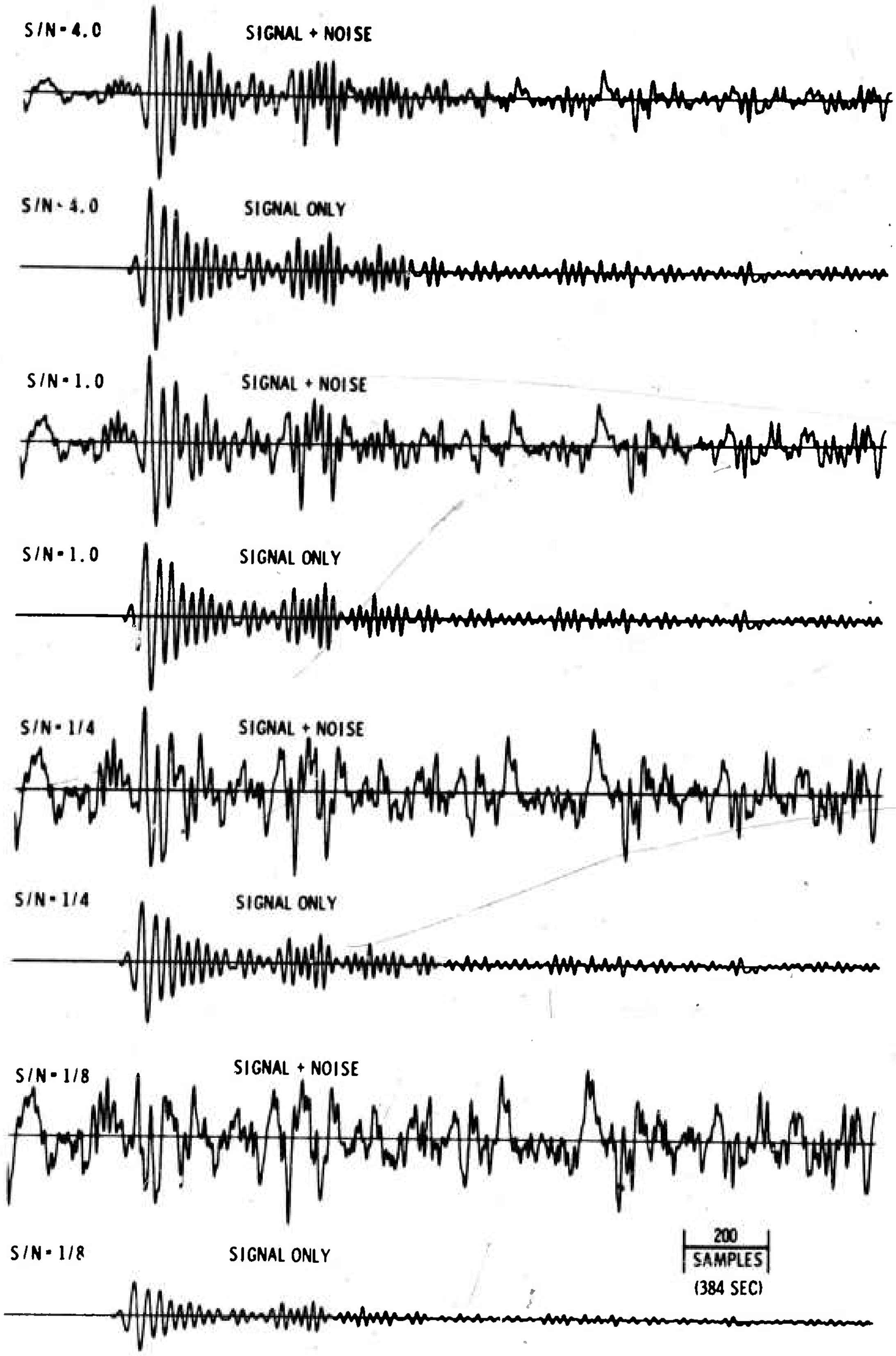

Figure 4. Signal Plus Noise and Signal Alone at Various S/N Ratios

SECTION III

EXPERIMENT AND RESULTS

The investigation concentrated on estimation of the noise spectrum and application of this spectrum to the data. In estimating the noise amplitude spectrum, the upper limit of 90 percent of the chi-square distribution was arbitrarily chosen. An estimated noise amplitude spectrum using 75 percent as the upper limit was generated to determine the sensitivity of the estimated spectrum to changes in its upper limit. Figure 5 compares the upper 90 percent and upper 75 percent confidence-limit noise spectra. Note that the noise spectra differ < 1 db over the range of interest, 0.0 to 0.15 Hz. Thus, the estimated spectrum is fairly insensitive to small changes in its upper limit.

Calculating the mean and variance of the maximum-likelihood estimators for the number of degrees of freedom b gives a mean of 4.88 and a standard deviation of 0.26 for these data. The small range of values indicates that perhaps a method other than the lengthy maximum-likelihood calculation can be used. Appendix A of reference 2 shows that if, for normally distributed white noise, the cosine transform A_k and sine transform B_k are also normally distributed and $A_k^2 + B_k^2$ is distributed as $\sigma'^2 \chi_2^2$, where σ'^2 equals the variance of A_k and B_k, then χ_2^2 equals the chi-square distribution with two degrees of freedom.

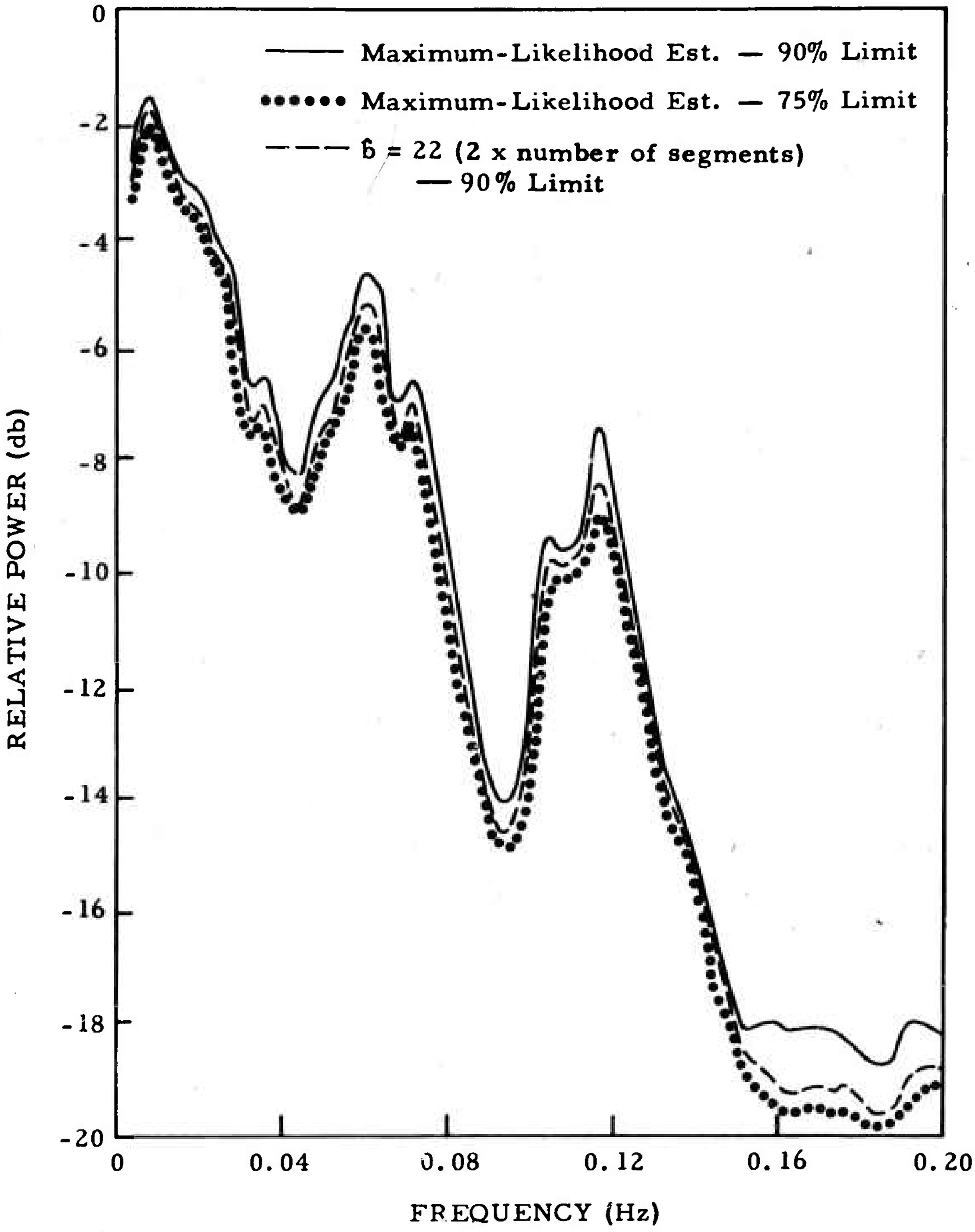

Figure 5. Estimated Noise Spectra for 256 Samples (491.52 sec)

Using this result with 11 segments of data gives b of 22. This is quite different from the average value of 4.88 from the maximum-likelihood estimation; however, the spectrum resulting from b = 22, as compared with the maximum-likelihood estimation for b shown in Figure 5, is < 1.0 db from 0.0 to 0.15 Hz. It therefore appears that a simpler spectral bound based on assigning the number of degrees of freedom in the χ^2 distribution as twice the number of segments would give very similar results.

The Nepenthe process, as originally conceived, subtracts the estimated noise spectrum from the amplitude spectrum of the segment to be treated and outputs this spectrum with negative values set to zero. At the lower S/N ratios, this affects considerably the output amplitude of the signal. See Figure 6 for Nepenthe on various S/N ratios.

To raise the amplitude of the output at lower S/N ratios and to compare more favorably in amplitude with the actual signal amplitude, a pass/no-pass technique was tried in which the estimated noise amplitude spectrum was compared point for point with the amplitude spectrum of the treated segment. If the amplitude of the treated segment's spectrum is larger, the entire amplitude value is passed; if the amplitude of the treated segment's spectrum is smaller, the value is set to zero. The resulting spectrum and the unaltered phase spectrum were then inverse-transformed and displayed as a time trace. As can be seen, this pass/no-pass technique is a zero-phase filter with infinite rejection at points where the estimated noise spectrum is larger than the treated segments and with a pass at points where it is smaller.

Figure 7 shows the pass/no-pass technique output for various S/N ratios. Note that this output compares more favorably with the signal at the lower S/N ratio and is similar to the bandpass filter (Figure 8). However, the signal output is distorted inasmuch as it is in the subtraction processor.

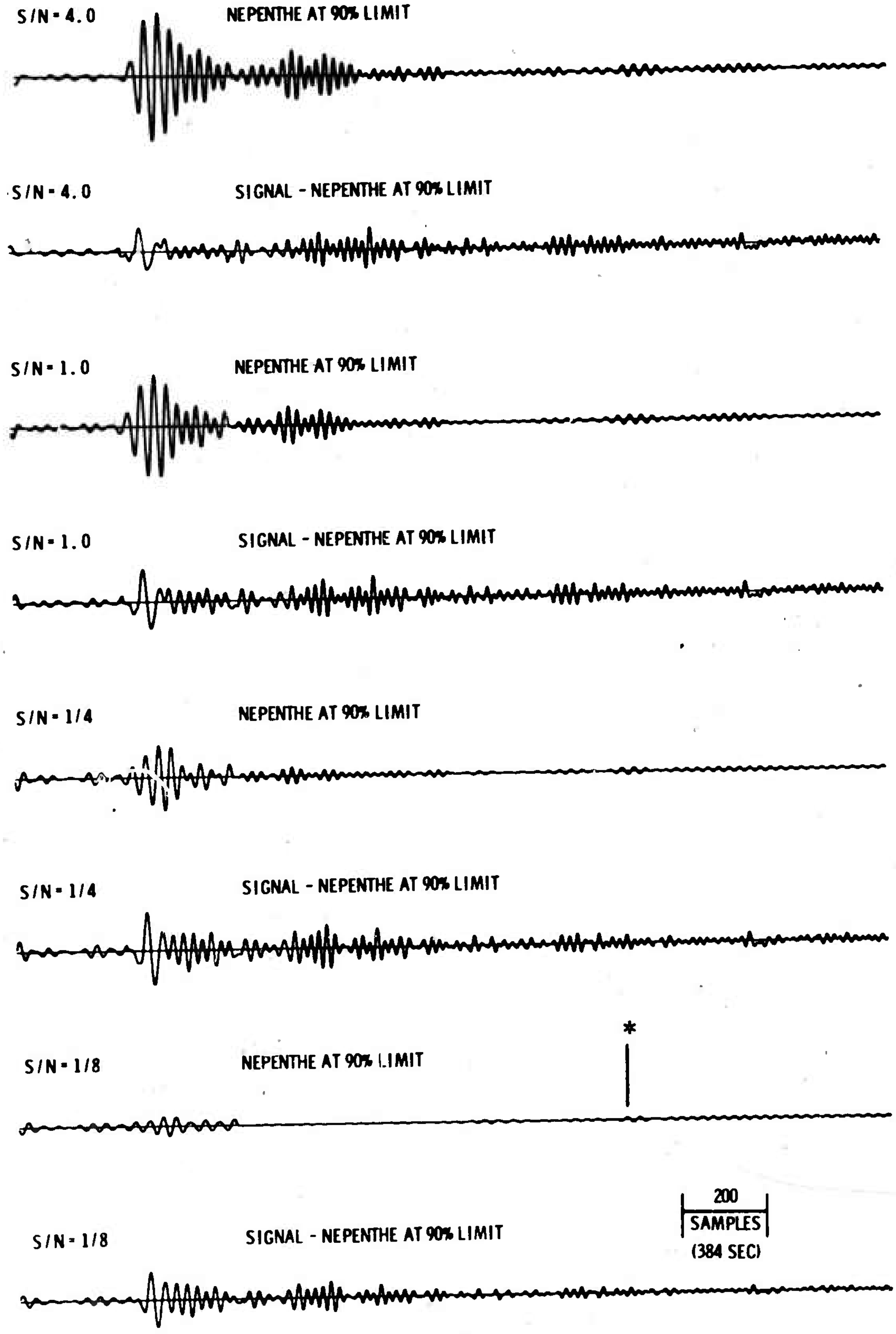

Figure 6. Nepenthe Output and Difference Trace for 90 Percent Limit at Various S/N Ratios

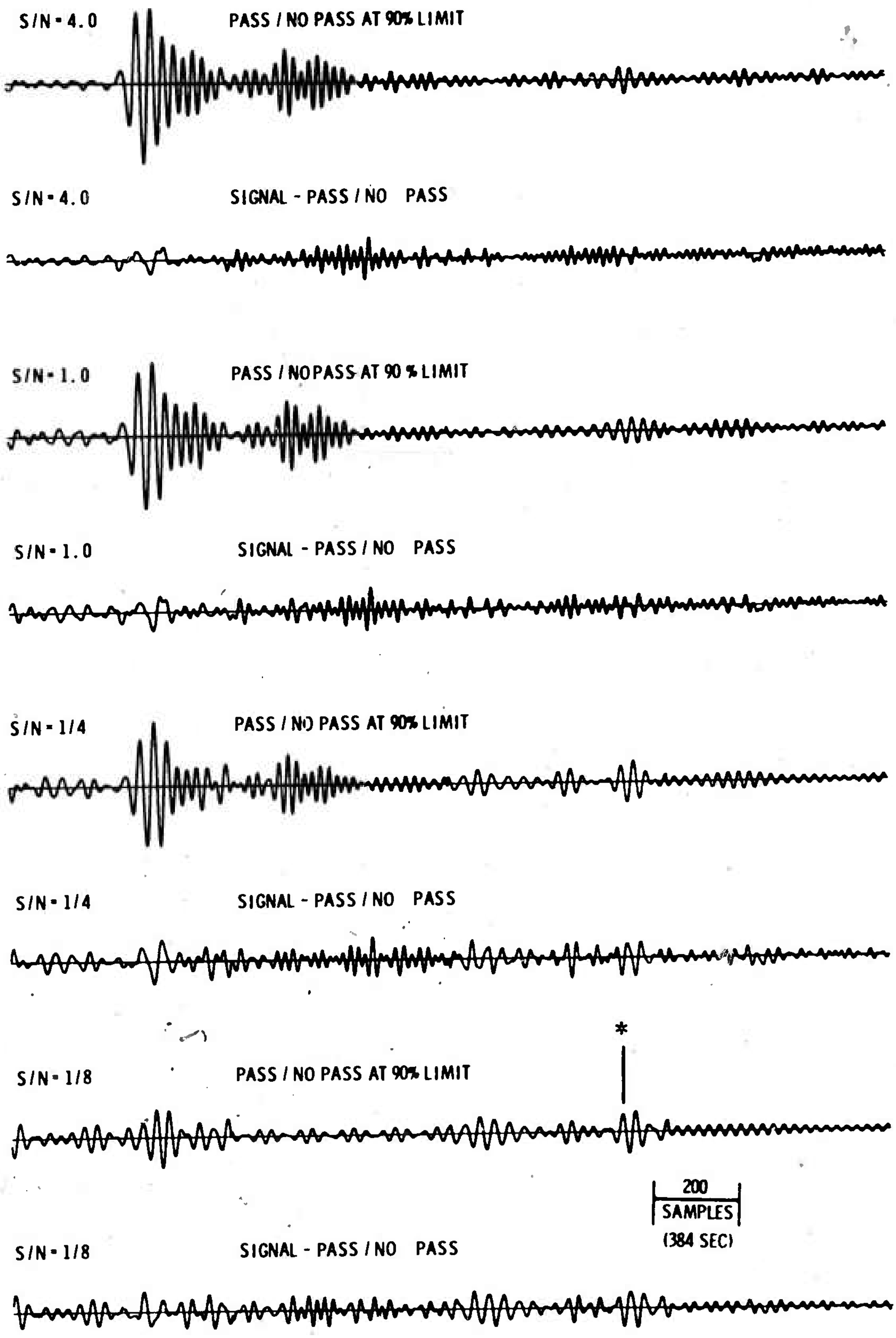

Figure 7. Pass/No-Pass Technique Outputs and Difference Trace for 90 Percent Limit at Various S/N Ratios

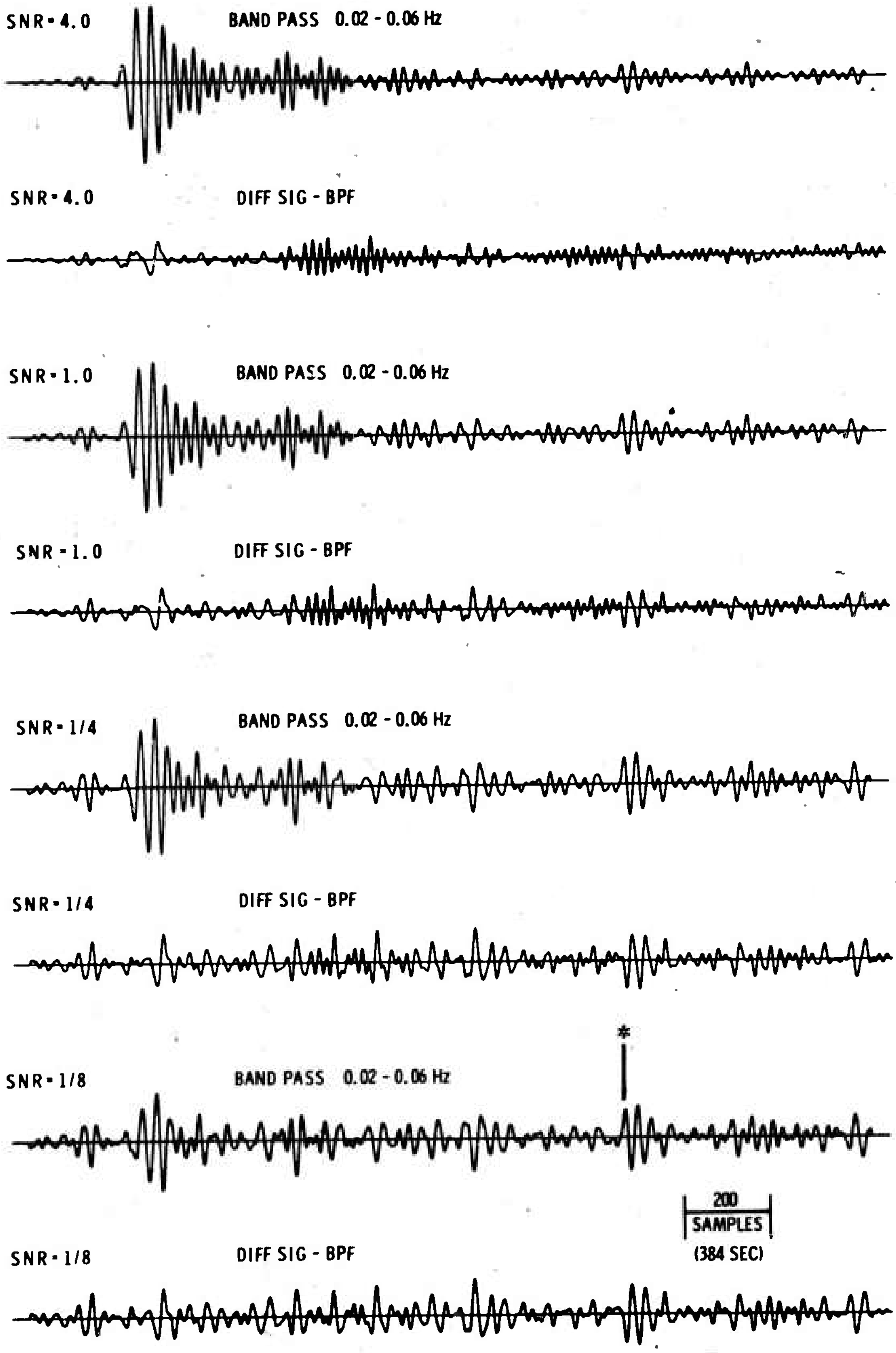

Figure 8. Zero-Phase Bandpass-Filtered Data and Difference Trace at Various S/N Ratios

Inasmuch as the signal changes rapidly with time, some features of the Nepenthe output were thought to vary with the position of the signal in the time gate, so the signal was shifted through the time gates and processed by Nepenthe; except for the time shifts, the outputs were identical. Thus, the position of the signal in the time gate is unimportant.

Because the treated segments are processed independently, a discontinuity may well exist in the waveform between the segments. To minimize this, an attempt was made to force the ends of the segments to zero; the method was to place the 256-point data segments in the center of a 512-point window, filling the remaining 256 points with 128 points of zeros on either side of the data. The data were then processed as if 512 points long. On the time-domain output, the data were truncated to 256 points again. It was hoped that putting the zero values on each end of the trace during the processing would force the output to be near zero at the ends of the segments; however, the discontinuities incurred by processing with 256-point segments were not severe and the 512-point segments made very little change.

From the time-domain output of the various processes, it is evident that the Nepenthe subtraction and the pass/no-pass techniques are at least as good as a bandpass filter at the higher S/N ratios. At the lower ratios, however, this processor also distorts signal waveform.

The ability of the Nepenthe or pass/no-pass processor to detect and output the signal depends on the relative noise levels during the signal period and the estimation period. If 5.00 degrees of freedom are assumed at a frequency f, for example, and the mean value of $P(f) = \bar{P}(f)$ in the estimator group, the noise amplitude spectrum estimator N(f) for the 90 percent upper $\frac{1}{P(f)}$ limit is

$$N(f) = [1.85 \, \bar{P}(f)]^{1/2} = 1.36 \, [\bar{P}(f)]^{1/2}$$

If, when the signal occurs, the noise $N_s(f)$ equals the mean value

$$N_s(f) = \bar{P}(f)^{1/2}$$

then, for the signal S(f) to be passed or detected,

$$S(f) + N_s(f) > N(f)$$

must be true and

$$S(f) + [\bar{P}(f)]^{1/2} > 1.36\,[P(f)]^{1/2}$$

$$S(f) > 0.36\,[P(f)]^{1/2}$$

$$\frac{S(f)}{N_s(f)} = \frac{S(f)}{[\bar{P}(f)]^{1/2}} > 0.36$$

If the noise amplitude is at the lower 25 percent limit of the distribution,

$$N_s(f) = [0.532\,\bar{P}(f)]^{1/2}$$

$$= 0.73\,[\bar{P}(f)]^{1/2}$$

$$S(f) + N_s(f) > N(f)$$

$$\frac{S(f)}{0.73[\bar{P}(f)]^{1/2}} > \frac{1.36[\bar{P}(f)]^{1/2}}{0.73[\bar{P}(f)]^{1/2}} - 1$$

$$\frac{S(f)}{N_s(f)} > 1.86-1 = 0.86$$

For the noise at the lower 10 percent,

$$\frac{S(f)}{N_s(f)} > \frac{1.36}{0.322} - 1 = 4.23-1 = 3.23$$

However, for a 0.02- to 0.06-Hz signal window using 256-sample-point time gates, 20 frequencies must be considered. If the 90 percent criterion is used, the probability that all frequencies (if they are independent) lie below the 90 percent level is $(0.9)^{20} \approx 0.122$. Thus, the probability of detecting at least one signal frequency is > 0.878 — but this is also the probability of passing any frequency, including noise.

If the entire transform of 129 frequencies were used, the probability of passing at least one frequency approaches 1.0. In the pass/no-pass technique, passing a high microseismic noise peak would either give a false event or completely overwhelm the signal energy. In the Nepenthe process, this noise would be attenuated. For example, using a value of b = 5.50 percent of the noise above the 90 percent limit in the Nepenthe subtraction processor would result in an output amplitude of < 1.2 times the mean noise instead of 2.2 times the mean noise as provided by the pass/no-pass technique.

Figure 7 shows the occurrence of a false event in the pass/no-pass technique for an S/N ratio of 1:8. At the point marked * on the record, the bandpass filter, Figure 8, and the pass/no-pass outputs display a noise burst that is only slightly evident on the Nepenthe output. The Nepenthe subtraction process thus appears the best of the three outputs for detection — but distortion of the waveform must also be considered.

The Nepenthe process was not compared with matched filtering. The matched filter would be the theoretically best linear filter for predetection processing.

Distortion in the Nepenthe process is the result of suppressing the various frequencies comprising the signal (by differing amounts). If the signal is to be passed completely, all noise components must be at or above the upper 90 percent level, thus, a weak signal will almost always be significantly distorted.

The pass/no-pass technique also incurs some distortion due to zeroed-frequency values but, since the passed signal amplitudes are not subject to subtraction as in the Nepenthe processor, distortion tends to be less, depending on the noise level and the S/N ratio. See the S/N ratio of 1 in Figures 6, 7, and 8 as an example of this tendency.

SECTION IV

CONCLUSIONS

The use of a constant value for the number of degrees of freedom rather than a maximum-likelihood estimator in the noise amplitude spectrum estimation will reduce the noise-estimation calculation time while only slightly affecting the noise spectrum obtained. The noise amplitude spectrum estimation appears to be insensitive to changes in the upper limit from 90 percent to 75 percent.

The Nepenthe technique tends to distort the signal. The pass/no-pass technique probably distorts less but is more susceptible to false detection. The bandpass filter would be similar to the pass/no-pass techniques if the signal fell within the passband. The Nepenthe and pass/no-pass techniques are not bandlimited as is the bandpass filter, but their use with a bandpass filter for obvious noise areas seems reasonable.

Because of its signal distortion, the inclusion of Nepenthe in the repertoire of long-period processing programs at SAAC is not recommended. The bandpass filtering and matched filtering capabilities should be sufficient.

SECTION V

REFERENCES

1. Simons, R.S., W.R. Weber, and H.S. Travis, 1968: Preliminary Report on a Single-Channel Statistical Technique for Suppressing Long-Period Micro-Seismic Noise, Geotech Tech. Rpt. 68-25, Contract F33657-68-C-0734, Project VT-8703, 19 Jul.

2. Texas Instruments Incorporated, 1967: Detection of Discrete Arrivals in Mantle P-Wave Noise, Large-Array Signal and Noise Analysis, Special Sci. Rpt. 5, Contract AF 33(657)-16678, 6 Sep.

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